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Radiation Flux and Spectral Analysis of the Multi-Temperature Z Dynamic Hohlraum*

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Abstract

Experiments performed at the Sandia National Laboratories (SNL) Z-Machine, located in Albuquerque, New Mexico produce hot (~ 220 eV) plasmas. X-ray emission from the plasma is used to drive radiation flow experiments. Our standard plasma diagnostic suite consists of X-ray Diodes (XRD), silicon photodiodes, and nickel thin film bolometers. Small diagnostic holes allow us to view the hot plasma from the side, top axial anode side and bottom axial cathode side. Computer software has been written to process the raw data to calculate data quality, fold in detector spectral response and experiment geometry for emitted flux, calculate a multi-detector spectral unfold, and yield an equivalent time dependent Planckian temperature profile. Spectral unfolds of our XRD data generally yield a Planckian-like spectrum. In our presentation we will compare our diagnostic techniques, analysis, and results to more accurately characterize spectral unfolds in order to establish better drive conditions for our experiments.

I. Z-MACHINE AND DYNAMIC HOHLRAUM

The Z-Machine uses z-pinch technology as a driver for material equation of state experiments, radiation flow experiments, and inertial confinement fusion research.

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Experiments employing dynamic Z-machine hohlraums can achieve a peak axial drive power of (>13.5 TW) and drive energy of (> 135 kJ) [1]. One of the goals of the refurbished Z is to develop a high-power and high-energy X-ray source that is accurately characterized and reproducible. To accurately characterize a source the intensity, the axial source power and the relative power of the source need to be understood. The source uses a multi-stage dynamic hohlraum formed by cylindrical wire arrays imploding onto a CH₂ foam cylinder. A set of 36 Marx banks are discharged into 36 transmission lines which shape and synchronize the current pulse that drives the wire arrays [2]. The 20 MA current pulse drives the lower inductance outer array via $\mathbf{J} \times \mathbf{B}$ forces until it coalesces with the inner array. Both arrays are then driven onto the central foam cylinder creating a high-Z shell around the foam which prevents radiation from escaping. The impact of the arrays on the foam transmits a radially-convergent shock. The multi-Mega-bar shock fully ionizes the foam and radiates as a blackbody at > 200 eV temperatures. The top and bottom ends of the foam are open, thus, this radiation is free to escape out the cylinder axis. The axial radiation can be used to drive an external experiment package or the trapped radiation can be used to implode an inertial confinement fusion capsule imbedded in the foam cylinder

II. RADIATION TEMPERATURE MEASUREMENTS

The dynamic hohlraum source is created from a radially-converging shock. Thus, the size, shape, and flux are very time-dependent. Tom Sanford *et al.* used an x-ray framing camera to view the emission from one axial end of the dynamic hohlraum, see Figure 1. The shock is seen to converge as a strongly emitting wave to a hot core with a much colder annulus at peak power. Furthermore, Greg Rochau *et al.* reported that

measurements of the radially-averaged shock speed are reproducible to within 3% [3]. The dynamically evolving source motivates some thought into how one might accurately represent our measurement uncertainties for unfolds of the time-dependent radiation flux for source temperature.

In this paper, we discuss how to better represent the uncertainty introduced by making the assumption of a single temperature source versus the power radiated by a more complex source. While the dynamic hohlraum is made up of a continuum of temperatures, we use a simplified example that shows the unfold uncertainty for a two-temperature source in comparison to a single-temperature source.

III. UNFOLDING MULTIPLE TEMPERATURE REGIONS

In the past when detectors have looked at the source the assumption was made that the source could be modeled as a disk, with area A , radiating at a single Planckian temperature, T , with $P = A\sigma_{SB}T^4$, where σ_{SB} is the Stefan-Boltzmann constant and P is the radiated power. Drawbacks of this method occur in assuming an inaccurate source size and assuming Planckian sources for the detector fold. The assumptions are made that sources at Z are nearly Planckian with less than 9% of the energy being represented by photon energies greater than 1.5 keV [1]. Our analysis is going to take this a step further and treat the source as having multiple temperature regions, two for this case. The reason for this is attributed to the data collected from past dynamic hohlraum experiments. It has been observed that as the tungsten wire array cylindrically converges on the foam core it creates a high temperature shock. Before stagnation this shock is only a fraction of the viewing area that the detector sees. The rest of the area in view is the “colder” tungsten plasma and the un-shocked foam. Gated x-ray images as shown in figure 1 have

verified the existence of the multiple temperature regions in the hohlraum sources. As the shock converges onto the foam core it creates a shock that heats up the foam and creates a temperature gradient between the differing regions. The pictures of figure 1 show three moments as the “hot” shock converges through the colder region clearly showing multiple regions radiating at different temperatures.

FIG. 1. Inward radiating shock (lighter region) converging on the hohlraum foam core.

It is clear by the knowledge of this process and these x-ray images that a source radiating at a single Planckian temperature is an inaccurate assumption. Analysis has already been made for multi-temperature sources by Stygar [4] and Rochau [3] where both the wall temperature and a source temperature is seen by a detector. Here we extend this analysis by considering a source with a temperature distribution as a function of radius. We assume here that the source is radially bounded such that it has a fixed aperture with area A . Within the aperture, we construct a series of concentric rings that have different temperatures as a function of radius. The total time-dependent power $P(t)$ emitted by the area is simply the sum of the powers emitted by each ring i of area A_i at temperature T_i ,

$$P(t) = \sum_i A_i(t) \sigma_{SB} T_i(t)^4 \quad (1)$$

The equation shows explicit time dependence for the areas and temperatures, and neglects the dependence on emissivity. To illustrate the error that can be attributed to the assumption of a single source, we calculate a two-temperature source with fixed areas, i.e., $A = A_1 + A_2$. We're interested in how the uncertainty changes when the temperatures

are significantly different from one another for fixed area emitters. For constant areas, we can replace A_1 and A_2 , with αA and $(1 - \alpha) A$, respectively,

$$P(t) = \alpha \sigma_{SB} A T_1^4 + (1 - \alpha) \sigma_{SB} A T_2^4 \quad (2)$$

where α is typically a time-dependent area ratio, but we simply consider the constant area case here. We use values obtained from spectrally-calibrated x-ray framing camera measurements of the axial emission from the dynamic hohlraum. This data is converted to spatially-dependent temperatures. We bin the temperatures into two area regions that represent a hot and cold temperature. As a comparison, we take the power-averaged temperature for the entire radiation exit hole.

Using a single temperature unfold, methods outlined in references [5] and [6], for the power at the detector results in a temperature measurement that is lower than the peak temperatures in the source, as shown in Figure 2. For experiments that involve the use of foams or hohlraums, the single temperature unfold can oversimplify the spectrum. In particular, the high energy spectrum of the hot core within the colder annulus could alter experimental results when one considers the opacity of materials. Take, for example, the source at near stagnation TPX (CH_2) foam where we have a 130 eV temperature annulus surrounding a 280 eV core placed near a plastic target. The peak of the blackbody curve for the annulus is near photon energies of 366 eV, while the blackbody peak associated with the core is near photon energies of 790 eV. The TPX foam is opaque to the cold annulus, but is fairly optically thin to a large fraction of the core's spectrum. This means that if one were to try to run a simulation with simply a single-temperature (grey body) spectrum, we could end up with the wrong spectrum as input.

FIG. 2. Power output for different temperatures using different source models, with the peak temperature using two-temperature regions and a cold region of 50 eV showing as temperatures increase the higher energies dominate.

As a first step, we look at what happens with a single-channel detector. Assume this detector is not spectrally resolving and has a uniform response over all wavelengths. The detector averages all of the emission and outputs a single current. The power measured by this broadband detector is then converted to a single temperature. For a simple two-temperature source, the uncertainty in the single temperature unfold is dependent on the relative uncertainties in our two-temperature emission,

$$\frac{\partial T}{T} \approx \frac{1}{T^4} \sqrt{\left[\alpha T_1^4 \frac{\partial T_1}{T_1} \right]^2 + \left[(1-\alpha) T_2^4 \frac{\partial T_2}{T_2} \right]^2} \quad (3)$$

Figure 2 shows that as the powers increase for both systems the temperatures required for these powers are considerable different. For example, as shown by the graph in figure 2 at ten kilowatts of power, modeling the source as a single temperature only requires a temperature of approximately 175 eV while the two-temperature source achieves the same power with peak temperature of approximately 269 eV, an increase in the temperature by almost 49%.

Equation 3 shows the expected trend, for fixed areas. The hotter temperature dominates the spectrum when the areal differences are swamped by the T^4 dependence, for example

$$\text{when } T_1 \ll T_2, T \approx T_2 \left(1 - \frac{\alpha T_1^4}{4(1-\alpha)T_2^4} + \dots \right) \quad (4)$$

Simply put, a single detector that does not have spatial or spectral resolution cannot alone provide reasonable temperature measurements. Thus, we use multiple detectors with different filters to somewhat crudely spectrally-resolve the emission from the source.

Figure 3 shows a typical spectral response curve for a set of five different filters placed in front of carbon cathodes as used in a typical detector housing [7]. In this case, the filters are selected to provide spectral cuts: (1) a Kimfoil[®] filter for ~100-270 eV with a high energy response tail at energies greater than 400 eV, (2) a vanadium filter for ~200-500 eV with a high energy response tail at energies above ~700 eV, (3) a zinc filter for energies greater than 300 eV, and (4) a beryllium-parylene filter for energies above 400 eV. This filter set is somewhat optimized for sources that have temperatures near 150-175 eV.

FIG. 3. Spectral Response for five filtered photocathodes.

Increasing the number of filters and detector channels will reduce the uncertainty in temperature. The accuracy of temperature measurements made by increasing the number of detectors, without altering the number of filter cuts will, however, be limited by the spatial dependence of the source. As an example, to assess the amount of “error” we introduce in unfolding the dynamic hohlraum source emission as though it were a single temperature source, we start with the x-ray framing camera measurements of the axial emission from the dynamic hohlraum for several time-points (Fig. 7 from Ref. 1). Two areal regions are selected and average temperatures are taken. The temperature is then converted to a greybody spectrum and propagated to the detector position. The detector response file is used to convert the power in each photon bin to current produced by the photon bin. We integrate this binned current over spectrum to get the total instantaneous current. The currents for each detector are then used as input for the spectral unfold code described previously.

Consistent with expectations, we found that when the core of the TPX foam was near 265 eV, while the surrounding tungsten and TPX foam were 190 eV, the unfold calculated a temperature of 195 eV. We compare this to when the hot core temperature is 190 eV with the blackbody peak near photon energies of 535 eV. Without changing the areas or annulus temperature of 145 eV, our unfold temperature is now 150 eV. In the context of spectrally-dependent experiments, the filter set described here is insufficient provide an adequate resolution of the source. A view of the differences in treating the source as two distinct temperature regions as opposed to a single temperature is shown in figure 4. It can be seen that major differences in the intensity do not occur until the higher energy end of the spectrum.

FIG. 4. a) A plot of the folded two-temperature spectrums with the single temperature power approximation blackbody generated by the unfolding code, with the cold and hot two temps line using 145/190 eV and 190/265 eV folded blackbodies and a single temperature blackbodies of 150 eV and 195 eV, respectively. b) Percent error in intensity between the spectrum created from the two-temperature regions and the single temperature blackbody power approximation to that spectrum.

It can also be shown that the percent error between the single temperature blackbody assumption and the folded two-temperature approximation increases greatly at energies greater than a 1.5 keV. The folded two-temperature intensities were folded with filter and photocathode response with some geometry to generate an effective current this data was then put into an unfolding code to generate an approximate spectrum of which a single temperature blackbody of equivalent power could be fit. In calculating the percent error, figure 4, the assumption that the two-temperature approximation is the true, or accepted, value is made and the percent error between the single temperature blackbody of equivalent power is generated. The 'colder spectrums' line uses the two-temperature

regions of 145 eV and 190 eV and a single temperature blackbody of an equivalent power to the fit spectrum of 150 eV, while the ‘hotter spectrums’ line is the error between temperature regions of 190 eV and 265 eV with a single temperature blackbody of 195 eV. The error is evaluated using type A evaluation and treating each photon energy as an independent observation [8]. It is also interesting to note that as the power of the single temperature assumption overlaps the folded spectrum the error converges hinting to the possible use of a “notch” filter in the energy range of the convergence for a very accurate measurement.

Many experiments are used to validate some form of physics-based model in a simulation. For some experiments that are staged on top of the dynamic hohlraum source, the temporal and spatial dependence of temperature can affect the overall dynamics of the target. For example, using simulations similar to those shown by R. Peterson *et al.* in Ref. 9, H. Tierney *et al.* reported that the overall blast wave position for a spatially-dependent “hot core” source advanced the blast wave position by 100 to 150 microns from the predicted position for a colder spatially-uniform source due to the spectral differences [10].

IV. CONCLUSION

It is reasonable to use a single temperature unfold under specific conditions: (1) when the detector system has multiple channels with some spectral resolution, (2) where the source is spatially uniform, or (3) when the differences in temperatures are more significant than the areal differences. We showed in figure 2 that a single temperature unfold neglects higher energy emission spectra of complex sources when there is a spatial dependence on

temperature. This is most evident at high photon energies where the total number of photons tends to be small. As shown in figure 4, the difference in unfolded emission from the actual source spectrum becomes increasingly large above 1.5 keV. This shows that input spectrums generated from the single temperature fits used in hydro codes may not adequately calculate where energy is being deposited and neglects preheat produced by the higher photon energies. For as-shot simulations the underestimate could manifest itself as an under-driven simulation if the materials being driven by the source have opacity dependencies at soft x-ray energies. The principal conclusion of this study is that interpreting the spectrum with broadband detectors is difficult and requires a good understanding of the overall dynamics of the source. Using knowledge of the spatial dependence as well as a careful selection of filter cuts can reduce temperature unfold uncertainties for multi-temperature sources.

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